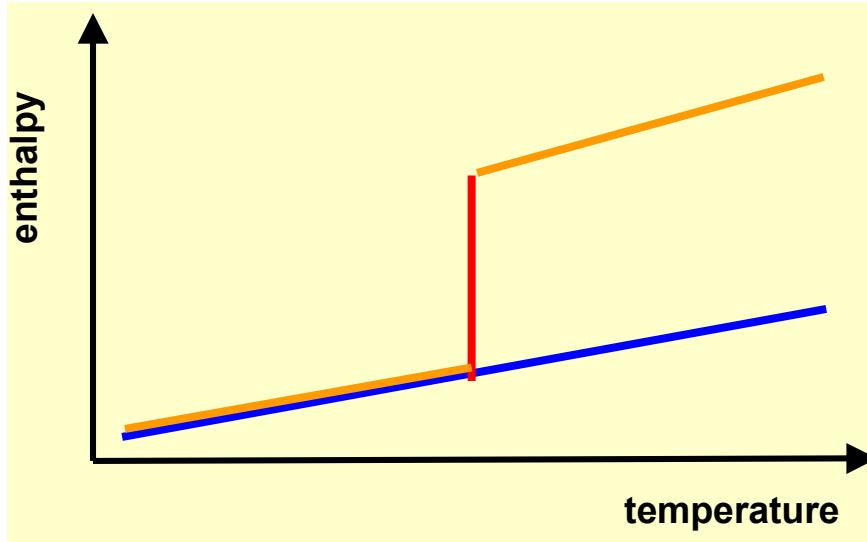


Phase - Change Storage Systems

Rainer Tamme
DLR - German Aerospace Center
Institute of Technical Thermodynamics

- **Introduction**
- **Previous activities and experiences**
- **Obstacles and solutions**
- **EG / PCM Approach**

Phase - Change Storage Systems



Definition

Thermal energy storage during phase change, preferably by melting process

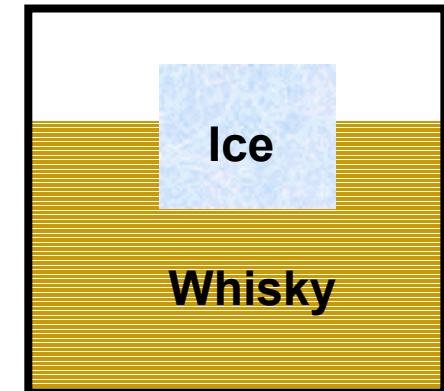
High storage capacity at small temperature variations

Latent heat storage

Most activities directed to low temperature applications

- cold (ice) storage
- space heating
- heat protection
- temperature stabilizing

Example



PCM Storage for Parabolic Trough Plants

Heat Transfer Fluid - HTF	Synthetic Oil	Water / Steam
Temperature range in °C	250 - 400	250 - 450
Operation pressure in bar	10 - 20	50 - 150



HTF Oil is cooled ~ 100 K

HTF Steam is cooled ~ 150 K

Single PCM cannot meet this requirements

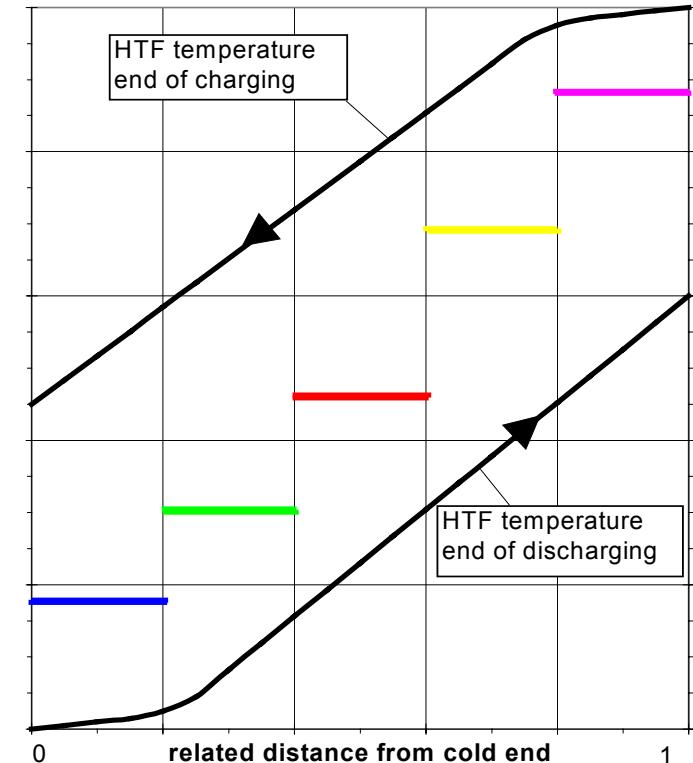
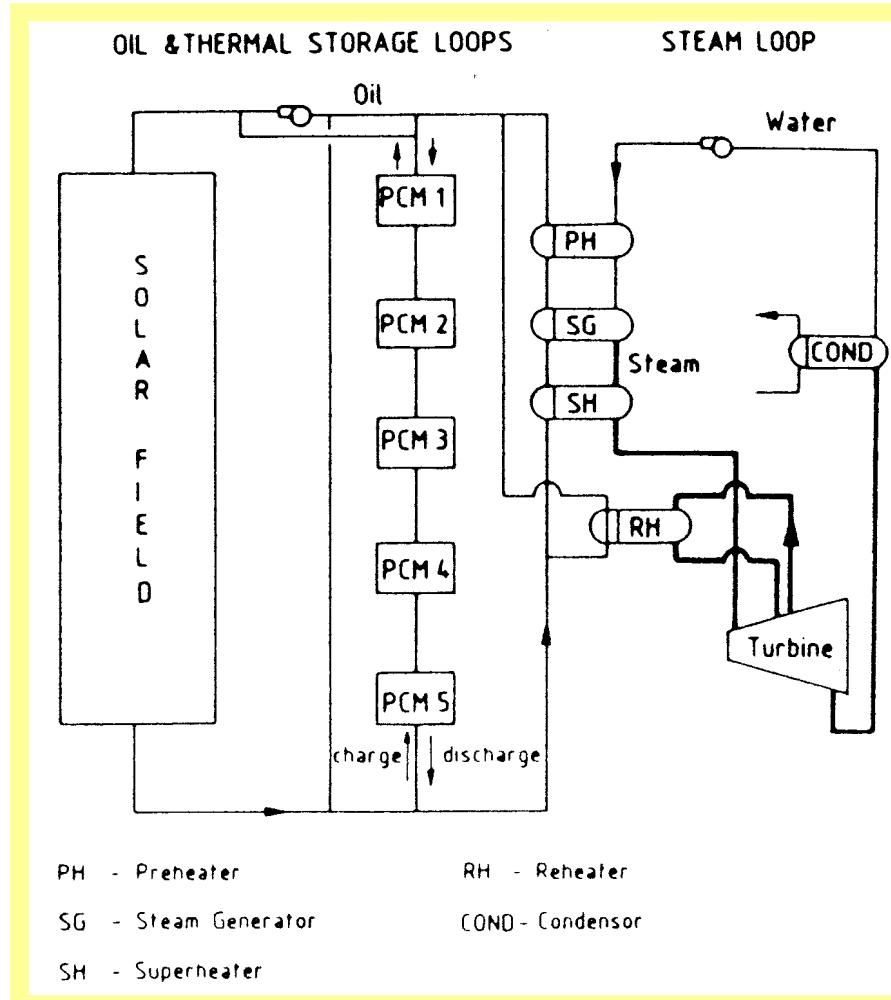
Phase - Change Storage Systems

Selected Phase Change Materials - PCM

PCM	T _{Melting} °C	ΔH _u [kJ/kg]
NaNO ₃	310	174
NaNO ₂	282	212
NaOH	318	158 (316)
KNO ₃	337	116
KOH	360	167
NaOH/ Na ₂ CO ₃ (7,2%)	283	340
NaCl(26,8%)/NaOH	370	370
NaCl/KCL(32,4%)/LiCl(32,8%)	346	281
NaCl(5,7%)/ NaNO ₃ (85,5%)/Na ₂ SO ₄	287	176
NaCl/ NaNO ₃ (5,0%)	284	171
NaCl(5,0%)/ NaNO ₃	282	212
NaCl(42,5%)/KCl(20,5%)/MgCl ₂	385-393	410
KNO ₃ (10%)/NaNO ₃	290	170
KNO ₃ /KCl(4,5%)	320	150
KNO ₃ /KBr(4,7%)/KCl(7,3%)	342	140

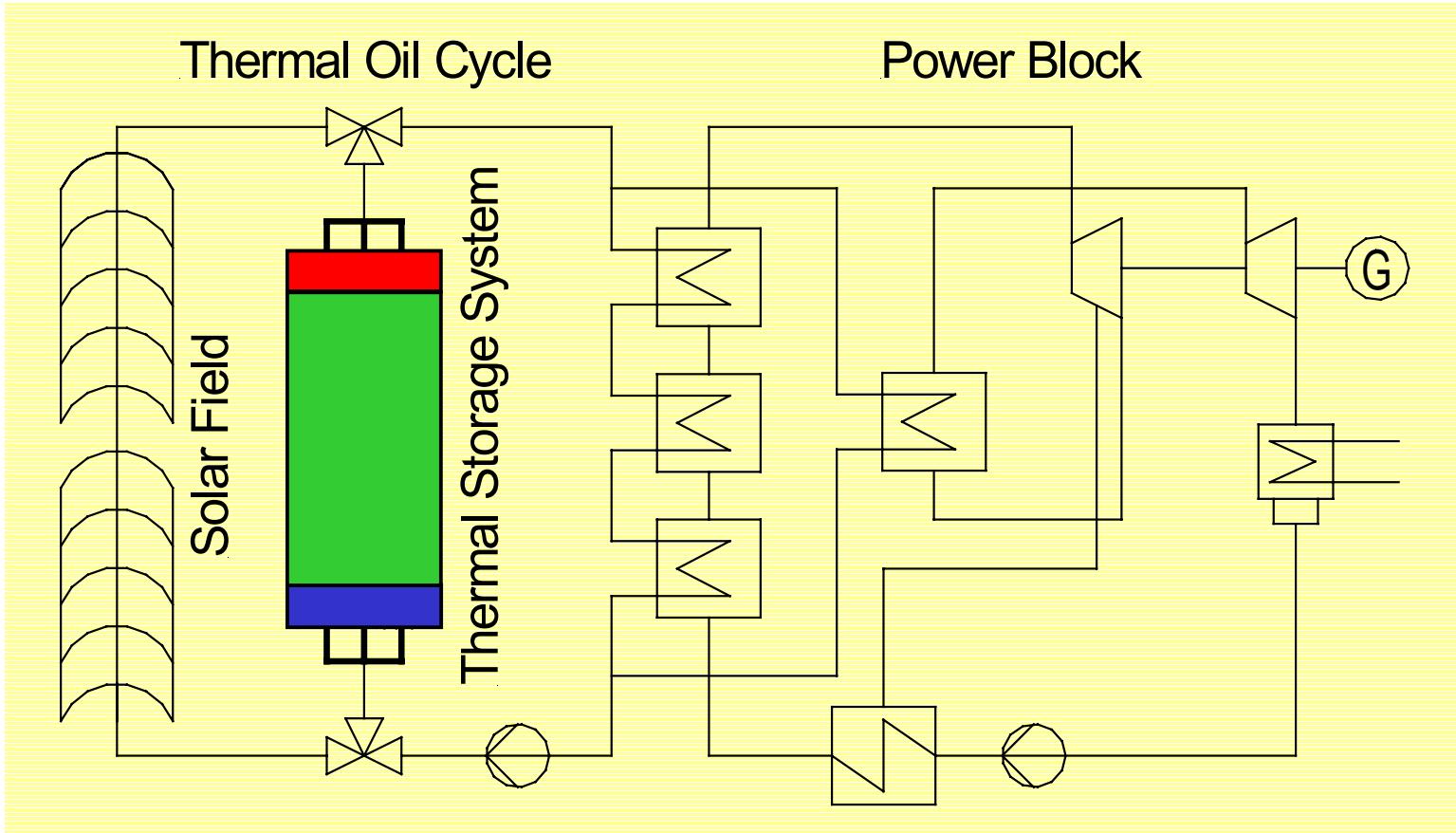
Phase - Change Storage Systems

LUZ proposal for Solar Plant with Cascaded PCM Storage (1990)



Phase - Change Storage Systems

**DLR - ZSW proposal for Solar Plant
with Hybrid - PCM/Sensible/PCM - Storage (1993)**

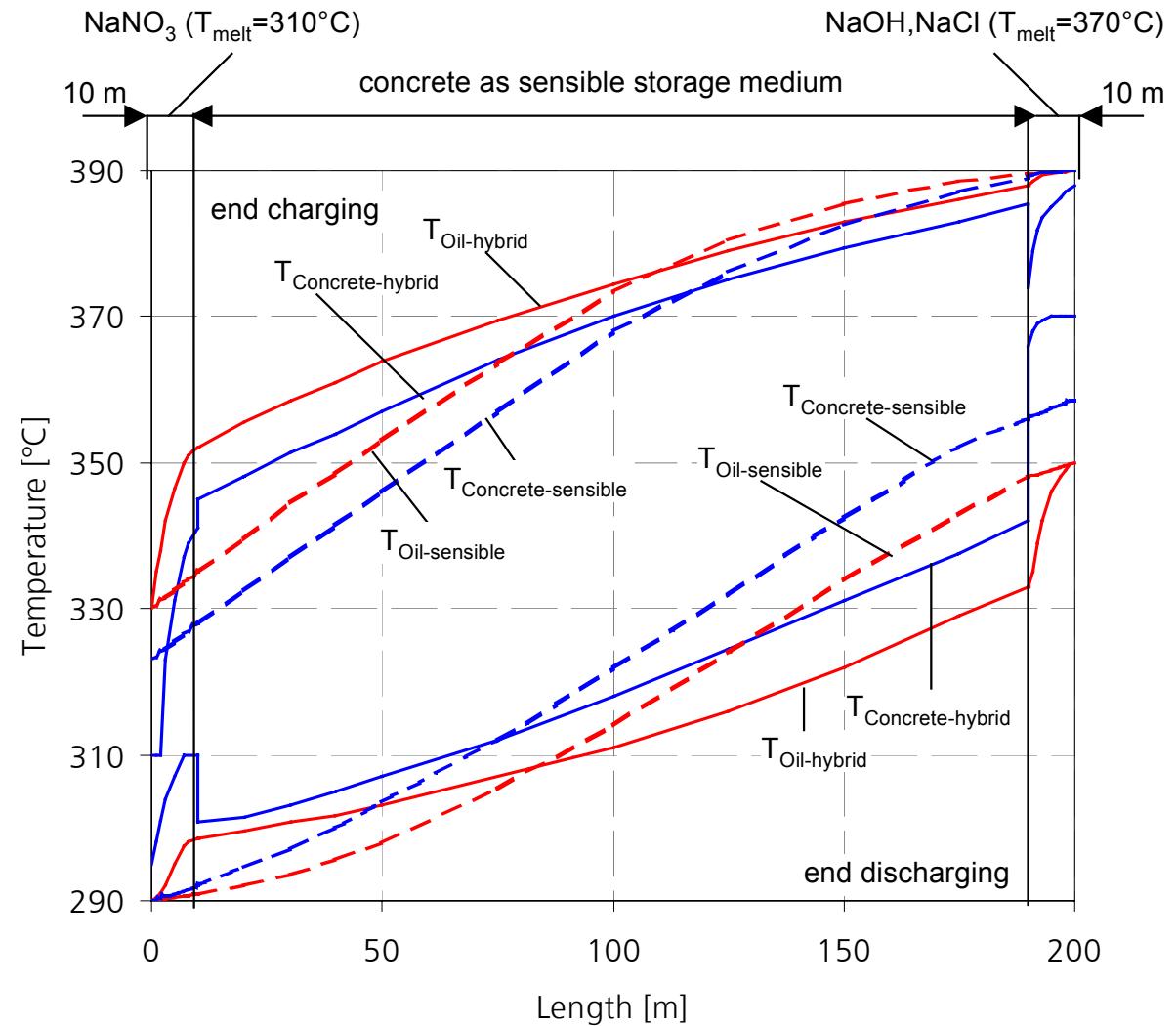


Phase - Change Storage Systems

Temperature distribution
200 MWh_t
3 h charging/1 h discharge
Synthetic Oil as HTF

Sensible Storage
Concrete
HTF

Hybrid Storage
PCM/Concrete/PCM
HTF



Phase - Change Storage Systems

Resulting Material Consumption for Both Systems

200 MWh_t - 3 h charging/1 h discharge - Synthetic Oil as HTF

	Sensible Concrete	Hybrid NaNO ₃ -Concrete-NaOH/NaCl		
Number of parallel tubes	24370	16260		
Storage volume	5574 m ³	Sensible	PCM	Total
Storage material mass	13544 to	3347	372	3719
Tube mass	1314 to	8133 to	745 to	8878
HTF mass	358 to			877
			?	239

what is the performance ?
what are the cost ?

Phase - Change Storage Systems

PCM Storage Modules tested at DLR and ZSW¹⁾

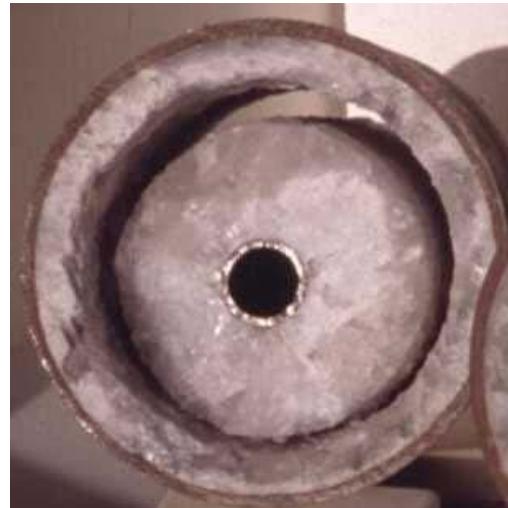
Test Module	PCM Material	Melting Temperature [°C]	Salt Mass [kg]
double tube internal tube diameter: 25mm / 18mm / 12mm	NaNO ₃	305	60
double tube internal tube diameter: 25mm	90% NaNO ₃ /10% KNO ₃	265 - 293	60
double tube internal tube diameter: 25mm	40% NaNO ₂ 7% NaNO ₃ /53%NaNO ₃	142	60
multiple tube array 7 tubes; 18mm diameter	NaNO ₃	305	540
buckled plate array 5 plates 505 x 1800 mm	NaNO ₃	305	850

¹⁾ Center for Solar Energy and Hydrogen Research, Stuttgart

Phase - Change Storage Systems



Tubular System



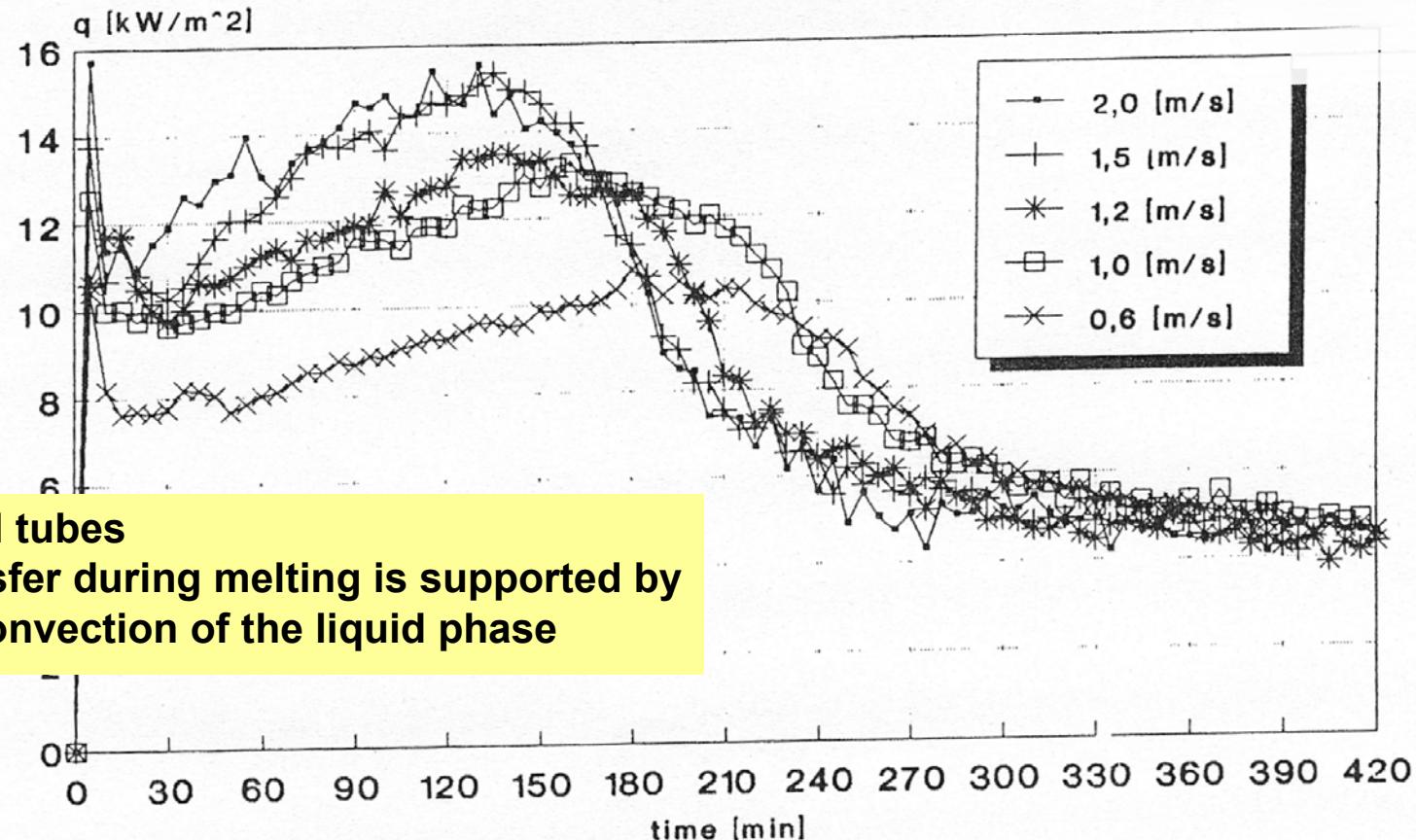
**Double Tube
Segment**



Segment of Buckled Plate

Phase - Change Storage Systems

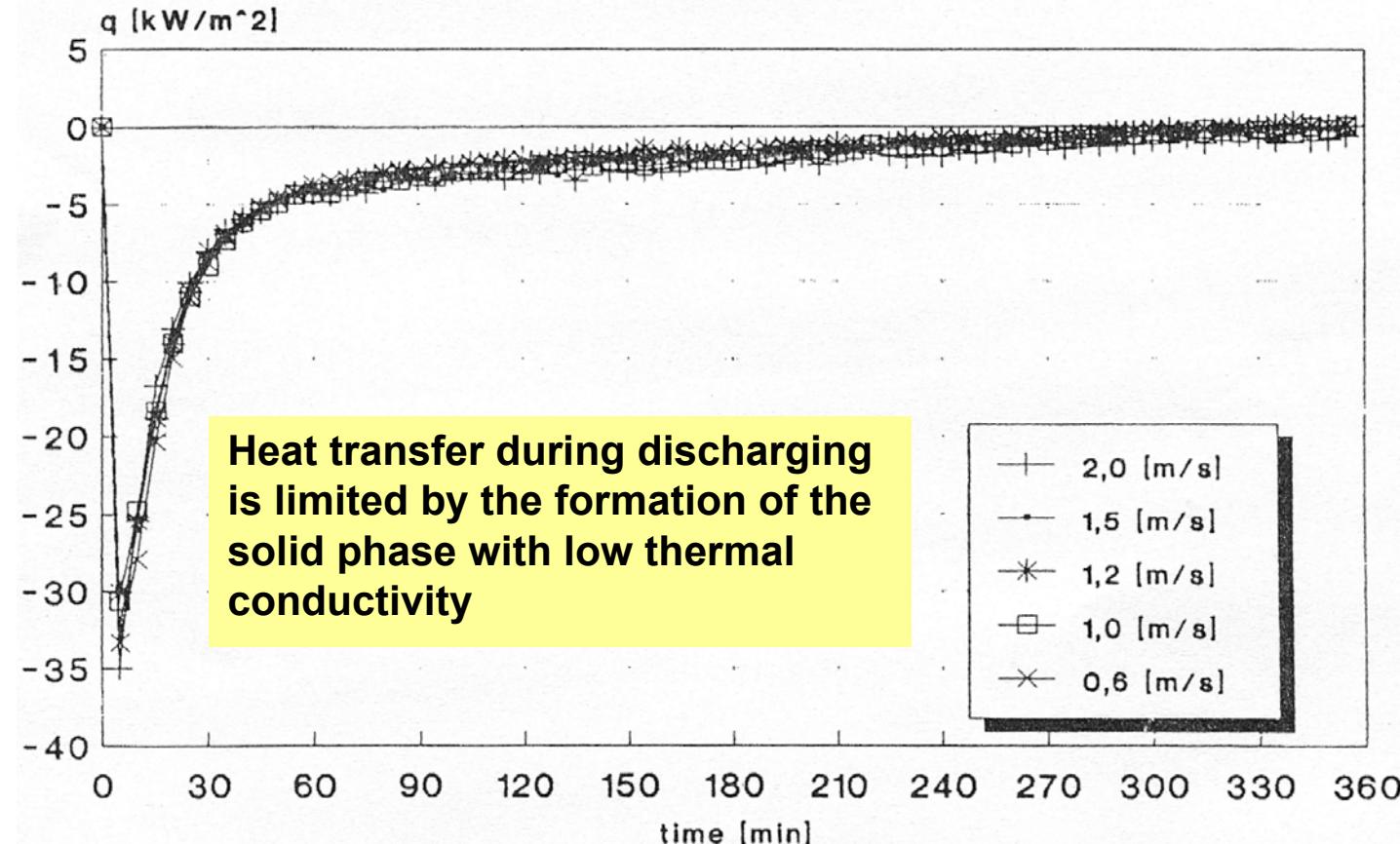
Heat flux densities
during charging of 90% NaNO₃/10% KNO₃ from 250 to 350 °C



Double Tube; 25 mm tube diameter; HTF velocity 0.6 to 2.0 m/s

Phase - Change Storage Systems

**Heat flux densities
during discharging of 90% NaNO₃/10% KNO₃ from 350 to 250 °C**



Double Tube; 25 mm tube diameter; HTF velocity 0.6 to 2.0 m/s

Lessons Learned

- ↶ **Straight forward design will not lead to an efficient and economic storage technology**
- ↶ **PCM has not is an intrinsic value
Storage concept and material is caused only by economic aspects
which means specific cost, reliability and scalable design**
- ↶ **PCM storage can only be applied commercially
if heat transfer limitations can be solved**

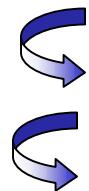
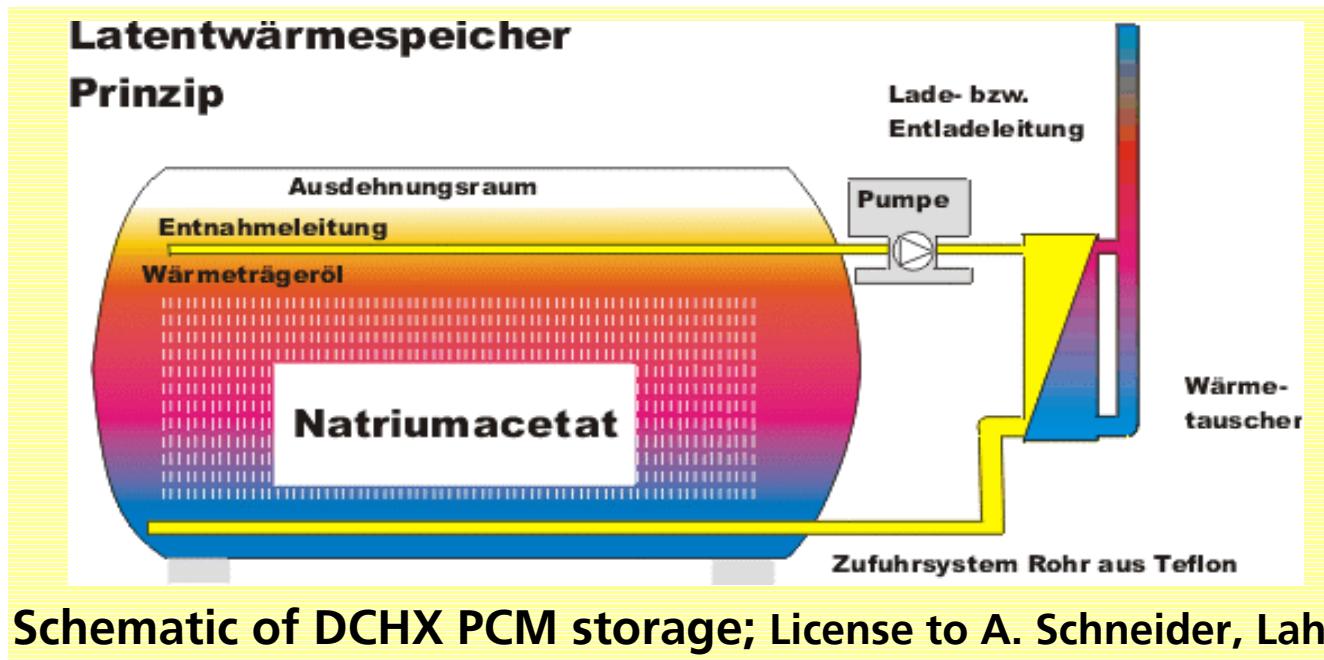
Approaches to overcome the heat transfer limitations of PCM's directed to:

- ↪ Direct contact heat exchange - DCHX  No solid heat exchanger wall
- ↪ Micro encapsulation of the PCM 
  Composite with high λ matrix
 Small PCM dimensions
 high specific surface
- ↪ Protection of heat exchanger surface against formation of solid PCM
- ↪ Influencing the melting/solidification process of the PCM

Phase - Change Storage Systems

Direct contact heat exchange - DCHX

1980-1990 DLR development of Oil /Salt-Hydrate system



Extension to high temperature ?

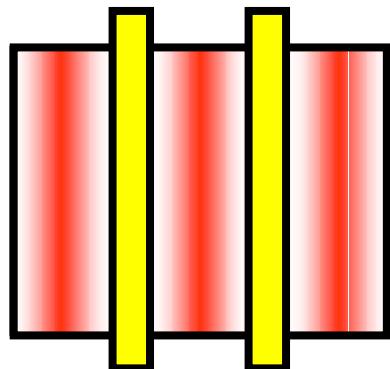
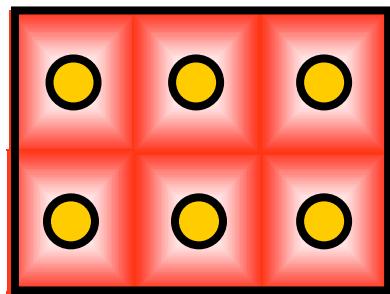


Will lead to pressurized storage vessels for oil HTF trough plants

Phase - Change Storage Systems

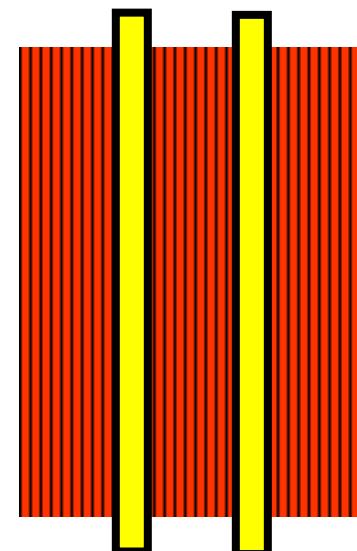
Encapsulation Approach

Conventional
Approach

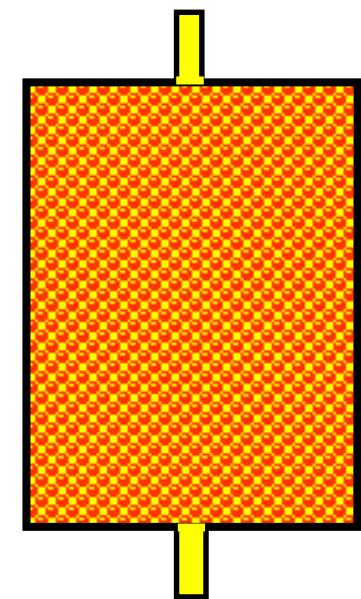


Micro
Encapsulation

Expanded Graphite - PCM
composite material



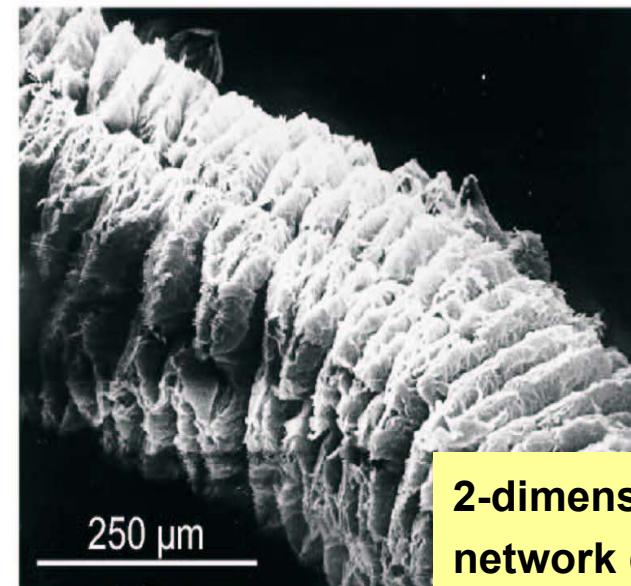
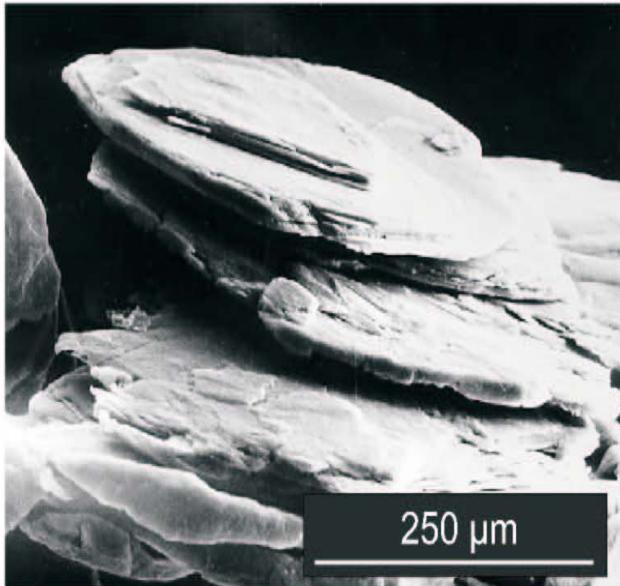
Macro
Encapsulation



Phase - Change Storage Systems

Formation of Expanded Graphite Matrix

expansion process - formation of expanded graphite worms



graphite salt $\xrightarrow[\text{thermal shock}]{(1000\text{ °C})}$ expanded graphite

2-dimensional graphite network determines thermal conductivity of the any composite material

tap density: 600-700 g/l

$\xrightarrow{\text{expansion factor 100 - 300}}$

tap density: 2-7 g/l

Source: SGL Carbon AG

Phase - Change Storage Systems

Production of Expanded Graphite matrix

continuous compacting of expanded graphite worms



production line for graphite matrix

standard sheet format: 1 m x 1 m
1.5 m x 1.5 m

standard sheet thickness: 1 - 10 mm

range of area weight: 200 - 2000 g/m²

typical density range: 0.1 - 0.5 g/cm³

typical pore content: 75 - 95 vol.%

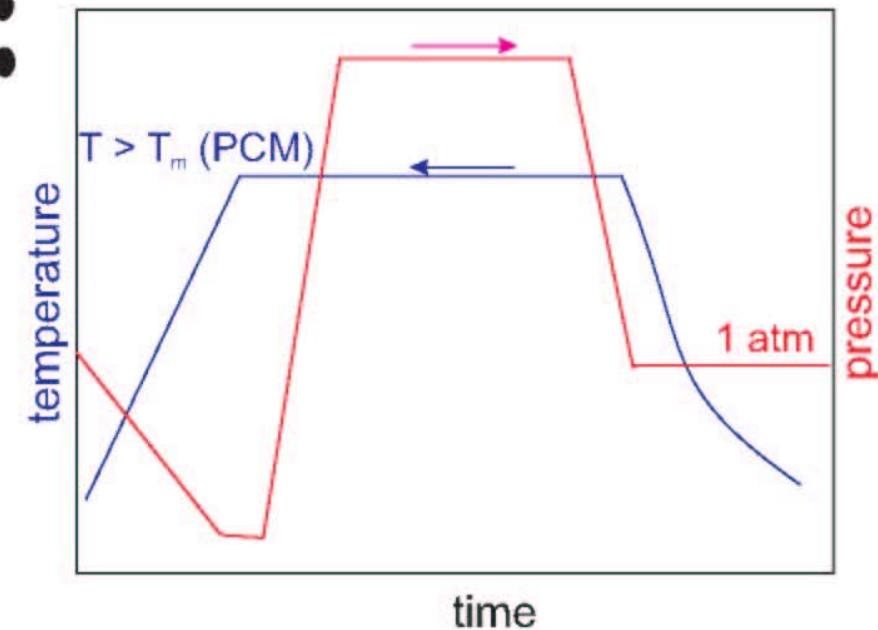
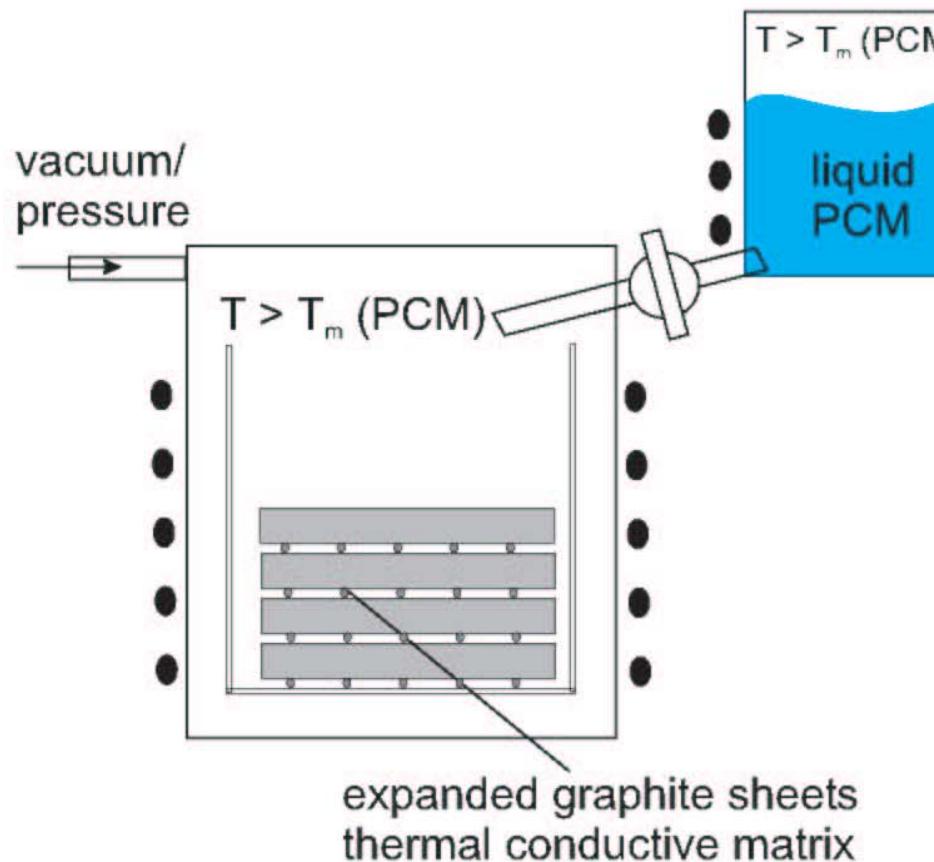
typical values:
sheet thickness: 10 mm
graphite density: 0.2 g/cm³ (10 vol.%)
pore content: 90 vol.%

Source: SGL Carbon AG

Phase - Change Storage Systems

EG /PCM Processing

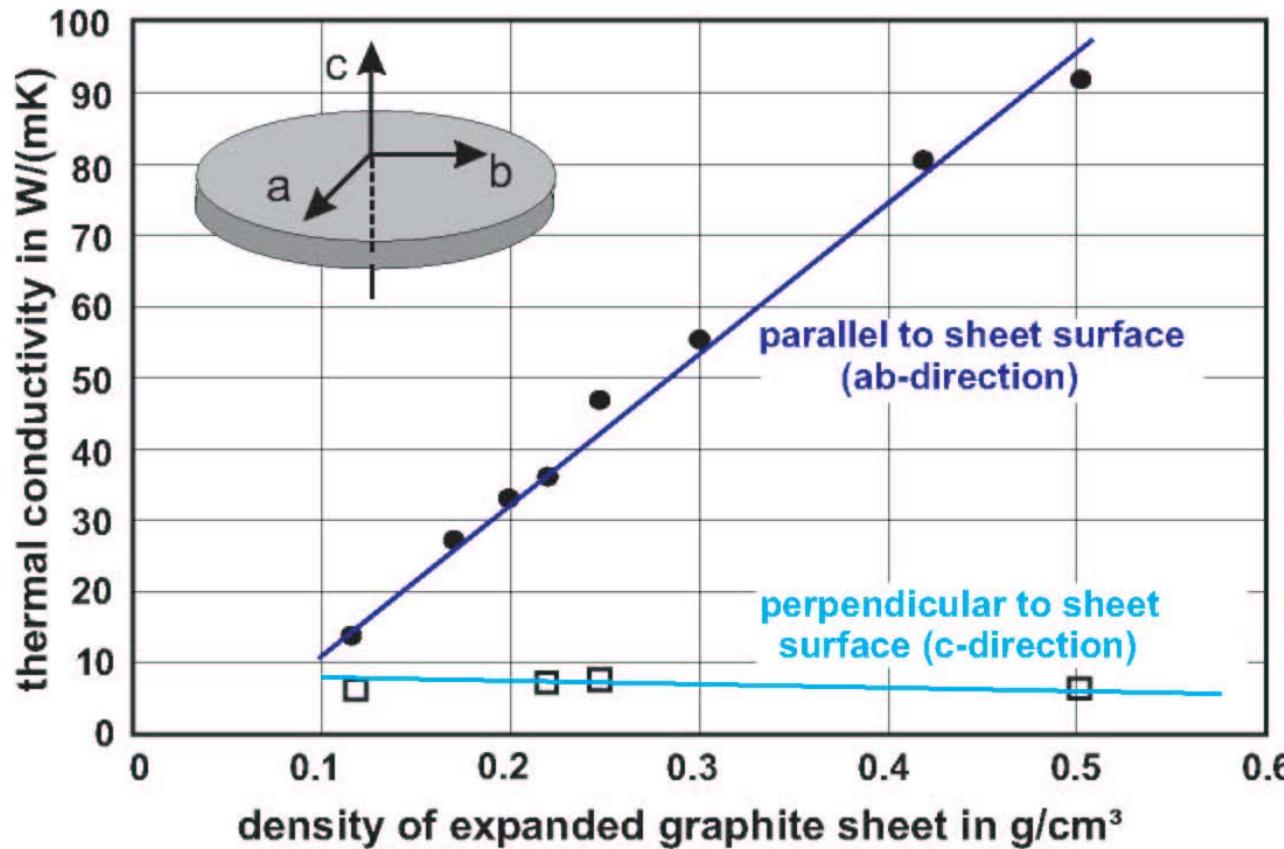
Vacuum/pressure infiltration process of the porous graphite sheets with liquid PCM



Source: SGL Carbon AG

Phase - Change Storage Systems

Anisotropic Thermal Conductivity of EG



EG / Paraffin Composite
15 % EG
80% Paraffin
 $\lambda = 20 \text{ W/mK}$ (ab-direction)

Compare:
 salthydrate: $\sim 0.5 \text{ W/(mK)}$
 paraffin: $\sim 0.2 \text{ W/(mK)}$

Source: SGL Carbon AG

Conclusions

PCM storage has achieved no or only minor technically application due non sufficient heat transfer

PCM encapsulation - micro or macro - offers attractive solution to solve heat transfer limitations

Expanded Graphite / PCM composite materials realized with Paraffin for low temperature applications

Transfer to high temperature with salt PCM needs further development